Security of Clean Energy Transitions

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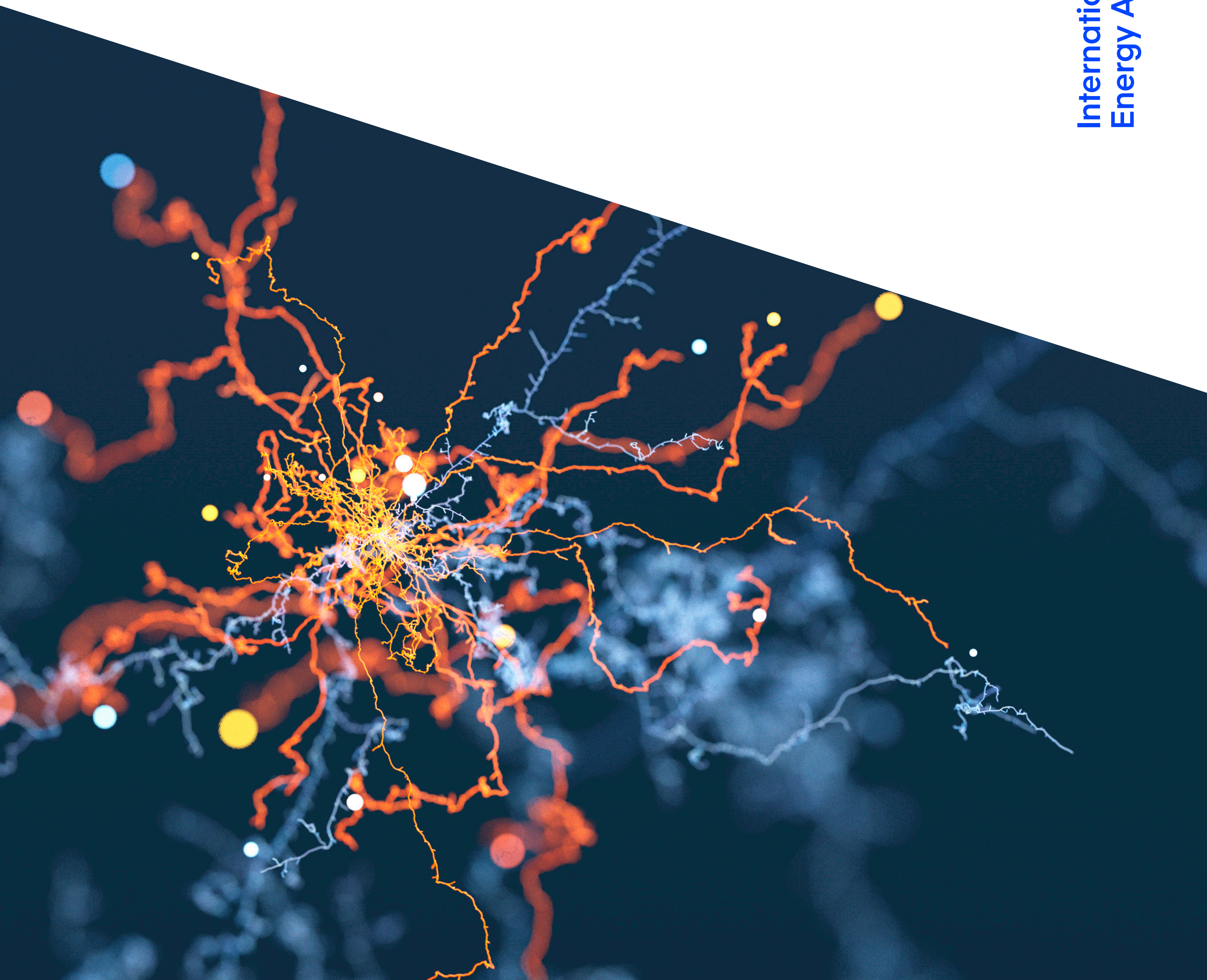
International Energy Agency



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INTERNATIONAL ENERGY AGENCY

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Abstract

This report examines the evolving nature of energy security in the context of clean energy transitions in general and on the pathway to net-zero emissions in particular. It highlights emerging energy security concerns and provides recommendations to foster international collaboration, notably within the Group of Twenty (G20).

In the context of Italy's G20 presidency, its Ministry of Economic Development requested the International Energy Agency (IEA) to undertake this *Security of Clean Energy Transitions* report. It aims to support discussions among the G20 countries and to provide insights and direction for the review and update of the G20 energy collaboration principles, which were endorsed at the G20 Brisbane Leaders' Summit in 2014.

Foreword

The energy sector holds the key to tackle the climate crisis – a great challenge of our times – and this is why an increasing number of G20 governments have pledged to reach net-zero emissions by mid-century or soon after. As our *Net Zero by 2050: A Roadmap for the Global Energy Sector* shows, energy security becomes even more important on the way to net zero. The defining elements of energy security evolve as reliance on renewable electricity, on critical minerals and digitalisation of grids grows and the roles of oil and gas change.

Since the IEA's creation in 1974, our core mission has been to promote secure, affordable and sustainable energy supplies to foster economic growth. While entering a new energy era, the IEA is ideally placed to continue to contribute. A central plank for energy security in a net zero world are investments in diversity, our best bet against security risks. Therefore, we need all technologies, including energy efficiency, renewables, low-carbon dispatchable generation, energy storage, smart grids and digital solutions, electricity networks and low-carbon fuels.

Governments and industry must boost resilience against new and more frequent threats. These include cyberattacks and extreme weather events, such as storms, floods, cold spells, heat waves and droughts. The energy system is increasingly vulnerable to disruptions in the supply of electricity, critical minerals and renewables.

We are grateful to the government of Italy for making a new paradigm for energy security a key priority of its G20 presidency and their invitation to the International Energy Agency to prepare this timely report. From Brisbane in 2014 to Rome in 2021, G20 collaboration on energy security has advanced with the focus placed on energy transitions, notably with the G20 troika of Japan, Saudi Arabia and Italy. I very much hope our report and practical guidance across seven principles will support effective international collaboration and inform decisions among G20 countries.

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Executive Director

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Executive summary

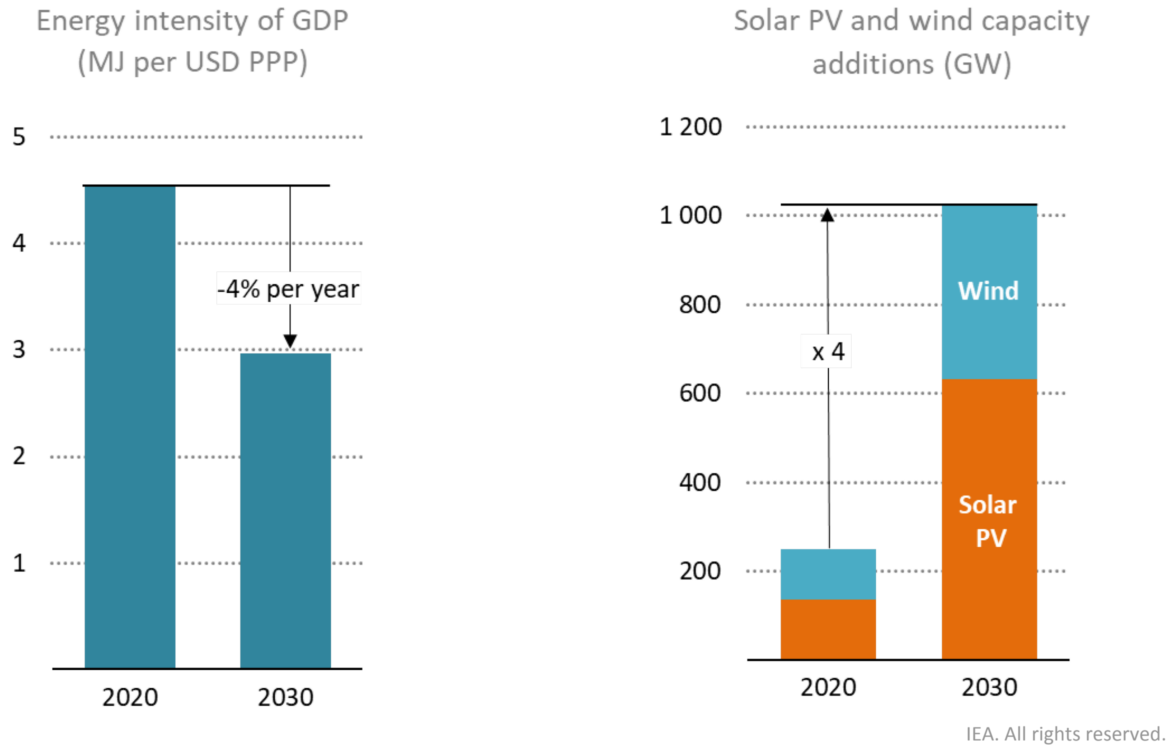
The global energy sector is going through a fundamental transformation as countries undertake clean energy transitions at various depths and speeds. The concept of energy security is becoming broader and more dynamic today than it has been in the past. Ensuring uninterrupted and reliable fuel supplies and critical energy-related commodities at affordable prices remains a fundamental policy goal. Traditional energy security risks have not dissipated, but as clean energy transitions progress new considerations arise.

On the way to net zero, energy security will only rise in importance. Countries that represent 70% of global emissions of carbon dioxide (CO_2) have pledged to reach net-zero emissions by mid-century or soon after. In 2021, the IEA *Net Zero by 2050: A Roadmap for the Global Energy Sector* (hereafter referred to as the *Net Zero Roadmap* in this report) outlined how the global energy system can shift towards net zero. Energy security concerns include probabilities of interruptions and induced price volatility, with oil and gas supplies being concentrated in a small number of low-cost producers with low-carbon footprints, a shift from the need to secure availability of fuels to critical minerals and a more central role of electricity security amid rising electrification.

Energy efficiency is the "first fuel" to achieve clean energy transitions in a secure manner. Efforts to strengthen and expand efficient technologies and practices need to be scaled up significantly, as energy savings and related behavioural changes have so far been much slower than needed.

Clean energy transitions in the period to 2030 will largely rely on variable renewables for electricity generation. Dramatic cost reductions in wind and solar photovoltaic (PV) power generation over the last decade are underpinning their record levels of expansion. Solar PV capacity increased by 135 gigawatts (GW) and wind by 114 GW in 2020, even as the Covid-19 pandemic dampened global electricity demand. The *Net Zero Roadmap* relies on the rapid scale up of solar and wind in this decade to four-times the levels seen in 2020. Renewable deployment brings major benefits for energy security, but needs a shift in policy and market design.

Energy efficiency, solar and wind are priorities to achieve near-term emissions reductions



Note: MJ = megajoules; GDP = gross domestic product in purchasing power parity terms; GW = gigawatts; PV = photovoltaics.
Source: IEA (2021), *Net Zero in 2050: A Roadmap for the Global Energy Sector*.

Electricity is becoming a main driver of the pathway to clean energy transitions and security of its supply is essential. The IEA report *Power Systems in Transition 2020* provides advice on how governments can integrate higher shares of variable renewables into the power system, as traditional dispatchable generation declines; boost resilience against new and rising threats, such as extreme weather events and cyberattacks.

G20 governments need to boost flexibility of power systems. First, this includes increased investment in dispatchable generation, including hydropower, nuclear and natural gas depending on national circumstances. Also to maximise the use of low-carbon generation sources to cut emissions and boost security. Second, it calls for cost-effective use of existing energy infrastructure by using low-carbon fuels, such as ammonia, hydrogen, biofuels and synthetic fuels. Third, it requires mechanisms to reward flexibility in electricity systems, and to expand energy storage, demand response and digital solutions as well as regional integration of electricity markets. In the period to 2030, existing resources will provide the bulk of flexibility and capacity contributions. The use of dispatchable generation sources that support clean energy transitions is critical.

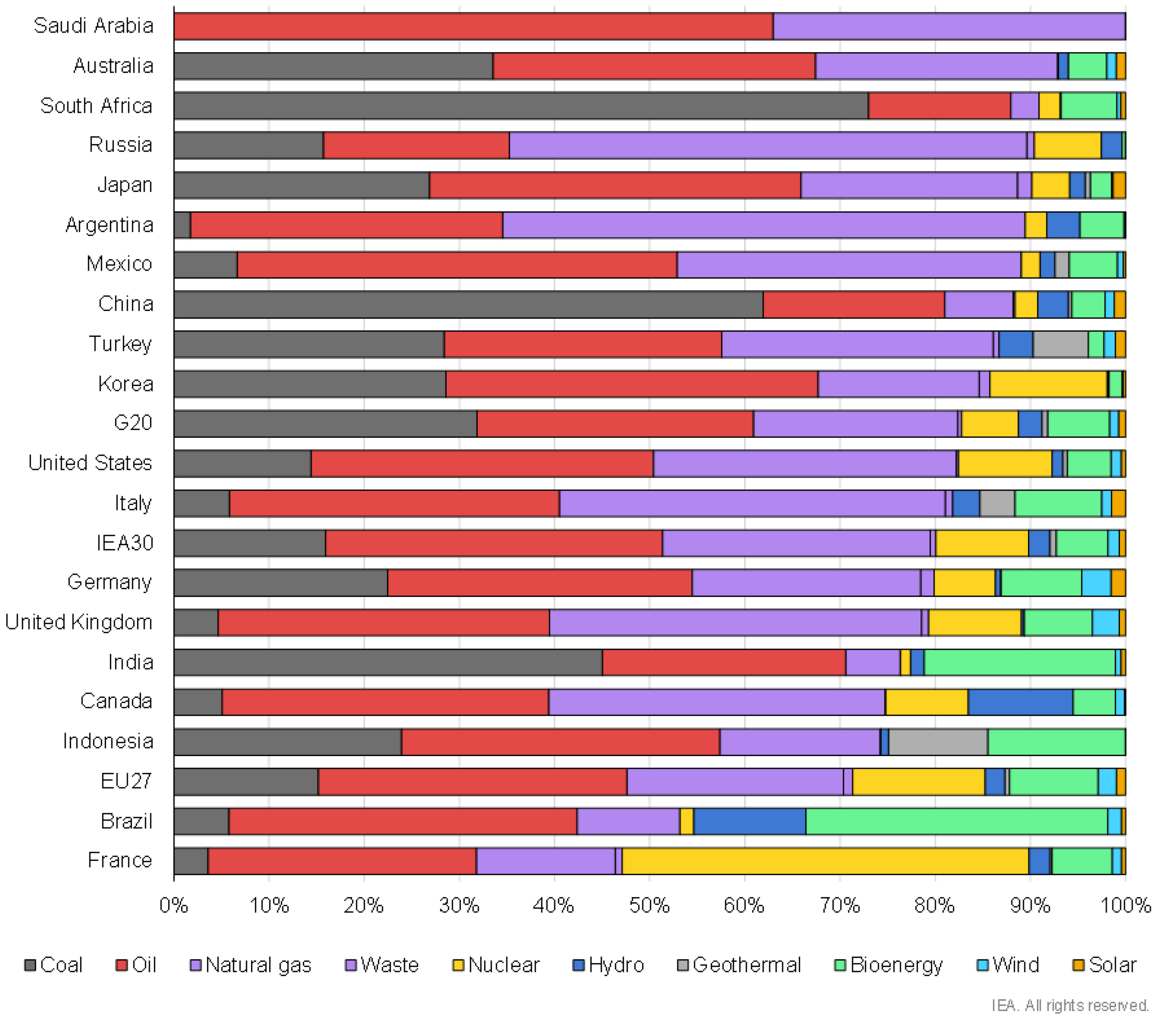
Governments need to promote investment in diversity - our best bet against security risks. In the period beyond 2030, diverse low-carbon technologies that currently are at the demonstration or prototype phase need to be developed and deployed, in particular dispatchable generation technologies that can add capacity and flexibility to power systems. Examples include various forms of storage and demand-side response technologies, which are projected to provide the bulk of electricity flexibility options by 2050. Carbon capture, utilisation and storage (CCUS) and advanced nuclear technologies such as small modular reactors are also important options for the clean energy transition. All effective technologies must be mobilised to achieve climate goals in a cost optimal and secure way. This requires that governments strategically direct and quickly increase spending on research and development. Developing, demonstrating and deploying clean energy technologies will boost the availability of innovative technologies as a hedge against technological uncertainty – this will enhance energy security.

Addressing emissions from existing energy-related infrastructure while making best use of their system value are critical elements of a secure clean energy pathway. All of today's power and industrial plants, buildings and vehicles – if they continue to rely on unabated combustion of fossil fuels – will generate a certain level of future emissions. Detailed analysis in the IEA *World Energy Outlook 2020* shows that if today's energy infrastructure continues to operate as it has in the past, it would lock in a temperature rise of 1.65°C. Fossil fuels dominate the energy supply of many G20 countries, as illustrated in the figure. Transitioning the existing energy infrastructure presents significant challenges.

Modifications to existing fossil fuel-related infrastructure offer opportunities for secure and affordable energy transitions. Coal- and gas-fired power plants can be retrofitted to burn fuels such as ammonia and hydrogen that contribute to security of electricity supply. In the transition, hydrogen can be blended into natural gas for distribution and natural gas pipelines can be repurposed to carry hydrogen or biomethane.

Policy makers need a comprehensive assessment of the inventory and value of existing assets from which to craft a framework that provides incentives for owners and operators to adequately address emissions, environmental impacts and security aspects. This includes to repurpose existing infrastructure assets and to mitigate adverse impacts on communities.

Total energy supply by source, G20 countries, 2019



Notes: IEA30 represents the member countries of the IEA and is shown for reference. EU27 represents the member states of the European Union and is a member of the G20.
Source: IEA (2021), *World Energy Balances*.

Oil and gas markets may experience heightened market volatility and concentration. This can happen if reductions in oil and gas demand are outpaced by decreases in supply due to lack of investment in existing fields, or if available supply is concentrated in fewer countries. Both the oil supply chain and the refinery sector will need to adapt to shifts in product markets, including more biofuels, and still ensure adequate oil product supplies. The IEA's oil emergency response system will continue to be a critical tool for ensuring oil supply security. However, it will need to be modernised as global oil demand is transitioning.

Global energy systems face increasing risks including changing climate patterns, cyber threats and the availability of critical minerals.

Governments need to address the rising significance of critical minerals for clean energy technologies. In 2021, IEA presented analysis on the *Role of Critical Minerals in Clean Energy Transitions* with six key recommendations to strengthen the resilience of global supply chains, promote technological advances, scale up recycling, maintain high environmental and social standards, and strengthen international collaboration between producers and consumers, including under the G20.

Digitalisation provides opportunities to enhance energy security but comes with new risks. Digitalisation supports improved energy planning, real-time monitoring, facilitating the use of distributed energy resources to provide services to power systems and response to critical situations. Governments need to ensure that emergency preparedness and response capabilities continue to be robust in a more digitalised and electrified system.

There is an urgent need for action by policy makers, utilities and stakeholders to enhance their energy systems' resilience to climate change. The electricity and energy system face increasing adverse impacts of climate change, resulting in rising global temperatures, erratic patterns of precipitation, sea level rise and more frequent or intense extreme weather events. More resilient electricity systems reduce damage and loss from climate impacts. Weather proofing of the energy infrastructure is part of a strategy to increase the robustness, resourcefulness and recovery of the system.

Clean energy transitions cannot succeed without putting people at the core. Governments should be prepared to address the impact of the energy transition on people and communities, notably with regard to employment, inclusiveness and equity. To ensure public support clean energy transitions need to enhance energy access, the security, affordability and reliability of energy supply.

Security and resilience of the energy system remain of fundamental importance as G20 countries transition to clean energy. Guiding clean energy transitions by boosting energy security, affordability and sustainable economic growth remains the critical task for G20 governments.

The *G20 Principles on Energy Collaboration* were established in 2014 by energy ministers, and endorsed by G20 leaders at their Brisbane Summit. This broad set of principles called for enhancing energy security through dialogue and collaboration on emergency response measures, high quality energy data, and well-functioning, open, competitive, efficient, stable and transparent energy markets that promote energy trade and investment. These principles were reaffirmed in 2018 at the G20 energy ministers meeting in Argentina, highlighting the importance of investment in infrastructure, the role of digitalisation and flexibility in the power sector, including the role of natural gas in the G20 countries. In 2019, under Japan's presidency, G20 energy ministers stressed the importance of resilience, protection and development of reliable energy infrastructure to prevent energy supply disruptions.

In a time of unprecedented international turbulence in the global oil market, an extraordinary meeting of G20 energy ministers was convened in April 2020 under Saudi Arabia's presidency. G20 ministers agreed to strengthen energy security and market stability by promoting market and data transparency, digital resilience and investment in the reliability of energy systems, which was endorsed by G20 Leaders at their Riyadh Summit. Italy holds the G20 presidency in 2021 and has set an objective to update the 2014 *G20 Principles on Energy Collaboration*, and broaden the energy security concept in line with evolving energy systems. Italy requested the IEA to support the discussions on broadening the energy security concept with a set of principles for G20 action.

As an update of the security provisions in the 2014 Brisbane principles, **G20 governments need to broaden their energy security and preparedness towards seven key principles for the security of clean energy transitions:**

1. Prioritise energy efficiency.
2. Secure integration of wind and solar PV in power systems. Ensure best use of existing sources of flexibility in power systems and enable effective smart grids and digitalisation.
3. Develop and deploy a portfolio of low-carbon generation sources to increase diversity of power supply and hedge against technology risks.
4. Ensure the cost-effective use of existing energy infrastructure for an affordable, secure and clean energy pathway.
5. Modernise oil security systems and boost transparent, open and competitive energy markets to accommodate traditional and emerging energy security concerns.
6. Prepare for new and emerging risks to energy security. Boost the resilience of global supply chains including for critical minerals. Foster digital security and climate resilience of energy infrastructure.
7. Promote a people-centred and inclusive approach to ensure energy access and reduce poverty, and foster economic diversification in producer economies.

1. Prioritise energy efficiency

Energy efficiency is the "first fuel". Doing more with less energy is fundamental to boost energy security. Energy efficiency is a key pillar to achieve emissions reduction goals and to support increased electrification of end-uses. It is a cost-effective strategy to enhance near- and long-term energy security at local, national and regional levels.

Energy efficiency delivers a wide range of social and economic benefits. Including, for example, lower energy bills for households and businesses, healthier living conditions, expanded employment opportunities, increased energy access, reduced greenhouse gas emissions and enhanced energy security. By dampening overall energy demand, efficiency can diminish reliance on imports of oil, gas and coal. Its job creation potential is large as the world recovers from the Covid-19 pandemic and its economic impacts, as demonstrated in the IEA *Sustainable Recovery Report.* A clean energy transition led by efficiency catalyses all the other transition actions making them more affordable and more achievable by moderating the overall scale of required investment and deployment.

A multitude of energy efficiency solutions for buildings, vehicles, appliances and industrial processes are available today. These mature technologies will play a key role in emissions reductions, particularly in this decade. The *Net Zero Roadmap* projects a world in which by 2050 the population expands by 40% but uses 8% less energy than today. Energy intensity improvements of 4% per year to 2030 – three-times the average rate achieved in the last 20 years – will be necessary. Given that global efficiency improvements have slowed in recent years, energy efficiency ambition and implementation need to be scaled up substantially. Beyond 2030, energy efficiency persists as a fundamental building block as the energy system will witness the large-scale of low-carbon technologies including hydrogen, carbon capture, with an even greater rate of electrification.

The Global Commission for Urgent Action on Energy Efficiency[1] underscored this urgency in June 2020 and recommended that governments be significantly more ambitious in setting both their short- and long-term efficiency targets and the policies and measures needed to realise the goals. These can be included in their Nationally Determined Contributions (submitted under the Paris Agreement), or take the form of

[1] Convened by IEA in response to the global slowdown of energy efficiency progress, the Global Commission for Urgent Action on Energy Efficiency was established in June 2019 at the IEA's Fourth Annual Global Conference on Energy Efficiency in Dublin, Ireland. The Commission has 23 members and is composed of national leaders, current and former ministers, top business executives and global thought leaders.

international collaborative initiatives. A stronger focus on climate action and net zero targets also creates the conditions for a "whole-of-government" focus on energy efficiency, as called for by the Global Commission.

Governments should lead by example and prioritise stringent efficiency standards and the implementation of energy efficiency policies throughout their operations. Action by the public sector and government investment in energy efficiency can accelerate deployment, stimulate innovation and provide effective signals to manufacturers and industry that demand for efficiency products and services is on the rise.

Energy efficiency measures and related job creation can be significantly ramped up by taking steps to promote increasing demand for efficiency products and services thereby boosting the market. Policies such as minimum energy performance standards stimulate demand for more efficient options and expand markets. Energy consumption labels help consumers to make prudent choices in purchases, save spending on energy and bolster markets for energy efficient options. Offering support to replace inefficient equipment with much more efficient models can accelerate the uptake and support markets for the improved goods.

Mobilising finance is necessary to scale up energy efficiency efforts. It needs to be part of a coherent approach in which financing and incentives are in step with measures to increase demand for energy efficient products and services.

Smart grids, digitalisation and related innovations are powerful tools to enhance system-wide energy efficiency. In particular, cities have the potential to act as drivers for digitally enabled clean energy transitions. Digitalisation can be especially beneficial in the world's rapidly growing cities where dense populations, expanding fleets of electric vehicles, and innovative district heating and cooling systems can work in synchrony to optimise energy supply and use. This is the focus of the IEA report *Empowering Cities for a Net-Zero Emissions: Unlocking Resilient, Smart, Sustainable Urban Energy Systems*, prepared for the G20 Climate and Energy Joint Ministerial session hosted by Italy in July 2021 (as is this report).

International collaboration can assist to harmonise approaches and to set energy performance standards. A broad exchange of best practices allows countries to share and learn about successful and unsuccessful approaches to instilling energy efficiency in their economies. It can accelerate progress globally. Of note is the Energy Efficiency Hub, a platform for global collaboration on energy efficiency established in late 2019.

2. Secure integration of wind and solar in power systems

A robust portfolio of renewables strengthens diversity and resilience, thus contributing to enhanced energy security. Renewable energy resources are widespread across the globe. They can be deployed at various scales and in some places can reduce or displace fossil fuel imports. Distributed energy production is located close to consumption centres and can contribute to resilience and security.

Global electricity generation from renewables is set to overtake that from coal-fired power plants by 2025, with solar photovoltaics (PV) and wind spearheading growth, underpinned by significant cost declines, widespread resource availability and strong policy support, as shown in the IEA *Renewables 2020*. Yet on the clean energy pathway, their deployment must further accelerate. The *Net Zero Roadmap* calls for annual additions of 630 gigawatts (GW) of solar PV and 390 GW of wind by 2030. Together, this is four-times the record levels set in 2020.

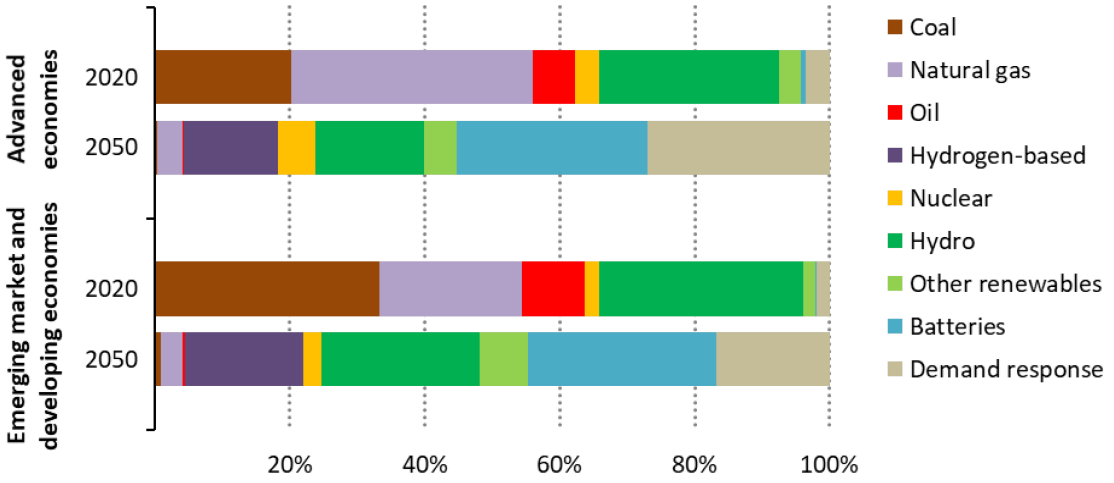
Today solar PV and wind are the cheapest sources of new power generation capacity in many markets. Their massive scale up and penetration in the system alongside changes in the shape and variability of electricity demand are increasing flexibility needs in power systems. Flexibility is becoming the main pillar of electricity security, covering a range of services that span time scales measured in seconds to hours, days and across seasons. Flexibility in power systems can stem from a variety of sources, including power plants, electricity networks, storage technologies and demand-response measures.

A large number of factors influence flexibility needs. These include, inter alia: the extent to which solar PV and wind can be deployed in a system-friendly manner; availability of grid capacity; network congestion points; profile of demand; seasonal weather patterns and the ability of system operators to accurately forecast and control wind and solar generation, as shown in the IEA *World Energy Outlook 2020*.

Conventional power plants provide the bulk of power system flexibility currently – both fossil fuel and dispatchable renewables. Coal-fired power plants are the main source of flexibility in many systems today, including China and India, while natural gas-fired power plants are the main source in European countries and the United States. Hydropower provides the biggest contribution to flexibility in some systems such as Brazil, Canada and the European Union. Nuclear power can provide power system flexibility in some cases, as for instance in France. In the European Union, strengthening interconnections is emerging as the central pillar of flexibility. Demand response and energy storage are becoming critical sources of power system flexibility in European countries.

The *Net Zero Roadmap* estimates that electric system flexibility needs to quadruple by 2050, as retirements of fossil fuel capacity reduce conventional sources of flexibility. By 2050, batteries and demand response become the prime sources of flexibility alongside low-carbon and dispatchable generation sources.

Electricity system flexibility by source, 2020 and 2050



Source: IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

Market and regulatory reforms should be tailored to reward effective forms of flexibility. Governments should take action to implement the power system infrastructure investment with priority.

During the coming decades, considerable amounts of dispatchable capacity will be retired as assets age or because new policies curtail their use in advanced economies, as shown in the IEA *Power Systems in Transition* report. This calls for maximising the use of low-carbon generation options, such as hydropower and nuclear, demand-response measures and storage options. As well, coal- and gas-fired power plants can be retrofitted/converted to biomass co-firing or ammonia use, and repurposed for more flexible operation with lower load factors. In this manner, they can continue to contribute to electricity security at lower emission levels during the transition.

3. Diversify the portfolio of low-carbon generation technologies

Diversity is the best guarantee of energy security. A well-diversified power generation mix can improve electricity security by mitigating risks arising from physical supply disruptions and price fluctuations.

Growth in wind and solar PV have boosted diversity in the global power generation mix. The scenarios in the *World Energy Outlook 2020* project this trend to continue such that by the late 2030s they account for the largest share of the global generation mix while electricity demand intensifies in the industry and transport sectors. However, this would represent a lower level of diversity in the power generation mix relative to today, which calls for investment in diversity. A top priority is to recognise the value of all low-carbon sources for global electricity security and to establish policy measures, incentives and market frameworks to remunerate both generation and flexibility services that they provide, as well to foster investment in maintenance and refurbishment of existing assets.

Hydropower is the biggest source of low-carbon electricity globally today. It provides a fundamental contribution to electricity security in terms of system flexibility. Both reservoir and pumped storage hydro systems are fully dispatchable and can be ramped up and down very rapidly in a secure and cost-effective manner, assuming adequate water resources. Moreover, pumped storage and reservoir hydro facilities are the largest form of electricity storage today, well ahead of the biggest available batteries. The *Net Zero Roadmap* builds on a doubling of hydropower output from the 2020 level by 2050. Yet, new hydro capacity additions peaked in 2014 and total installed capacity has been on the decline. IEA's *Hydropower Special Market Report 2021* projects that new hydro capacity installed in the period to 2030 will be 20% less than in the previous decade. So while new hydro capacity is expected to increase during this decade, it is well off track with the net zero path.

Accelerated deployment of new hydropower faces a number of important barriers. Access to land and water resources can be a major factor. Reflective of its size and long lead times, construction risks are significant and financing is complex. For existing hydro, the electricity market frameworks in many countries do not provide for or are insufficient to remunerate the services that hydropower offers in terms of flexibility and storage. Moreover, existing hydro facilities are ageing – more than 40% of the world's hydropower plants are more than 40 years old. Currently, neither market nor policy planning frameworks are adequate to attract the level of investment needed to refurbish and extend the operating life of ageing hydro plants.

Solar thermal and geothermal can provide dispatchable electricity with very high levels of annual capacity factors, thus strongly contributing to electricity security. However, investment is lagging and recent capacity additions represent less than 1% of total new renewable power annual installations.

Another important dispatchable renewable resource for flexibility of power generation is **bioenergy** (biomass or biogas). Availability of sustainable biomass can be a limiting factor for co-firing or even conversion of coal plants, especially for big units, and dedicated biofuel supply strategies and sustainability criteria are needed within the constraints imposed by bioenergy use in clean energy pathways.

Nuclear is the second-largest low-emission source behind hydropower. Nuclear power stations operate primarily as baseload generation and add to electricity security. Nuclear power contributes to cutting emissions from the electricity sector by doubling its capacity by 2050 in the *Net Zero Roadmap*. This implies that nuclear capacity additions need to reach 30 GW per year in the early 2030s – five-times the rate of the last decade.

Two regional pathways are evident. In the emerging market and developing economies, nuclear power output increases in the period to 2030; capacity totalling 42 GW was under construction at the start of 2020 (out of 62 GW globally). The People's Republic of China (hereafter "China") is on track to become the leader in nuclear power around 2030. It is one of the few countries that have included nuclear power, along with renewables, in the low-emission strategy in its Nationally Determined Contribution under the Paris Agreement. Notable programmes underway in the Russian Federation (hereafter "Russia"), India and the Middle East add to the expansion of nuclear power, according to the *World Energy Outlook 2020.* Whereas in the advanced economies, nuclear output is set to fall in the period to 2030 as the fleet of reactors age, few new plants are built and some countries phase out their nuclear capacity. At the start of 2020, about 20 GW of new nuclear power capacity was under construction in Finland, France, Japan, Korea, Slovakia, Turkey, United Kingdom and United States: otherwise there is limited projected additional capacity in the decade to 2030 in advanced economies, as set out in the *World Energy Outlook 2020*.

Lifetime extensions prolong the operational life of about 120 GW of nuclear capacity that otherwise would have closed by 2030. Lifetime extensions of existing nuclear plants are the lowest cost option for low-carbon electricity generation as shown in the *Projected Costs of Generating Electricity 2020*. Without lifetime extensions, investment needs in clean energy transitions would rise by USD 1.6 trillion in the decades to 2040 and heighten electricity security challenges, as outlined in *Nuclear Power in Clean Energy Systems.*

Nuclear power technologies have been evolving in recent years, not least to enhance safety. Several large-scale reactors with new designs have been completed recently. In addition, small-scale modular units are gaining support because they could address some challenges to the development of large reactors by reducing upfront capital investment, scaling projects to meet incremental demand, streamlining the construction process and driving down costs through standardisation and manufacturing (*World Energy Outlook 2020*).

Several G20 countries are leading the development and deployment of **carbon capture, utilisation and storage** (CCUS) technologies. CCUS can facilitate the transition to net-zero CO_2 emissions by:

- tackling emissions from existing assets; supporting a way to address emissions from some of the most challenging sectors
- providing a cost-effective pathway to scale up low-carbon hydrogen production rapidly
- and facilitating CO_2 removal from the atmosphere with bioenergy-fired generation capacity equipped with carbon capture and storage (BECCS) and direct air capture with carbon capture and storage (DACCS).

In the medium-term, CCUS technologies can help bridge clean energy transitions by retrofitting existing fossil fuel generation and industrial plants, as well as in the production of hydrogen from lower emission sources. Over time, the increased use of CCUS with BECCS and DACCS could make it a source of climate-neutral CO_2 for use in various applications, particularly synthetic fuels. In the *Net Zero Roadmap*, 50% of CCUS is applied to fossil fuel combustion, 20% in industrial processes and around 30% in BECCS and DACCS applications.

Low-carbon fuels, e.g. biomethane, hydrogen, ammonia, synthetic methane and natural gas fitted with CCUS, can enhance the flexibility of power systems by providing primary fuel input for dispatchable power generation with lower emissions levels than direct combustion of fossil fuels. They can also serve as short-term and seasonal storage capability in clean energy transition periods. Power-to-gas technologies (production of green hydrogen and synthetic methane from renewable electricity) can support the ramp up of hydrogen uses and supply chains.

The *Net Zero Roadmap* examines the role of **natural gas-fired capacity** in the power sector in the initial period of the pathway, notably in its displacement of coal-fired power plants. Today, natural gas meets a considerable share of seasonal energy demand swings in many countries and responds to short-term demand fluctuations resulting from variations in weather conditions and volatility of electricity markets. Gas-fired power generation is a key option for balancing power systems by providing back-up generation capacity to ensure grid stability and security of supply. In the longer term, gas-fired power plants need to be equipped with CCUS or retrofitted to use hydrogen or other low-carbon fuels to align with a net zero pathway.

System operators and gas suppliers need timely and transparent information on gas demand for power generation in order to manage critical gas contingencies. Flexible gas supply assets, such as spare pipeline capacity and fast-cycling storage are valuable for energy systems. Some flexibility services provided by current gas systems will be complemented and replaced by electrification, battery storage, improved energy efficiency and energy management systems.

4. Ensure the cost-effective use of existing energy infrastructure

Many of today's energy sector assets will be with us on the path to a cleaner energy future. These include a large number of capital-intensive and long-lived assets such as pipelines, refineries, coal-fired power plants, large hydro plants, buildings and urban infrastructure that can have technical and economic lifetimes of 50 years or more.

Clean energy transitions are not only about investments in efficiency improvements and new low-carbon energy sources, but also about the future of existing energy infrastructure. IEA analysis in the *World Energy Outlook 2020* estimated that if today's infrastructure, including power plants under construction, is operated as per past practices, it would lock in a long-term temperature rise of around 1.65°C. To mitigate emissions from existing assets, they would need to be retrofitted, repurposed or retired early.

IEA analysis finds that the electricity sector accounts for more than 50% of the total emissions that would come from existing assets; 40% of total emissions from coal-fired power plants alone. Industry is the next largest sector, with steel, cement, chemicals and other industry accounting for around 30% of total emissions from existing assets.

Large regional differences in emissions levels from existing assets are evident. Advanced economies tend to have much older capital stocks than emerging market and developing economies, particularly in the electricity sector, and existing assets will reach the end of their lifetimes earlier in those countries. For example, the average age of coal-fired power plants in China is 13 years, 16 years in the rest of Asia, compared to around 35 years in Europe and 40 years in the United States.

In the clean energy transition, existing coal- and gas-fired power plants may offer cost-effective options to provide adequacy and ancillary services in electricity systems. One option would be to equip a plant with CCUS to mitigate emissions. Another option may be to retrofit or repurpose existing plants to co-fire or switch to low-carbon fuels such as biomass, biogas/methane, hydrogen or ammonia.

Some coal-fired units have been repurposed to full biomass plants. The IEA estimates that 30% co-firing with hydrogen in gas-fired plants is possible, using current combustors with minimal modifications. Fully hydrogen-fired turbines are available. Up to 20% co-firing with ammonia in coal plants is being demonstrated, with a plan to increase the share of ammonia up to 60%. Coal- and gas-fired power plants can be transformed to synchronous condensers that can provide inertia to electricity systems, by removing the boiler and steam-related equipment and leaving the generator spinning free.

Existing natural gas infrastructure can support the cost-effective deployment of low-carbon gases, e.g. biomethane, hydrogen, and synthetic methane and their integration into energy supply systems. This will require development of a market model for the production, transport and trade of low-carbon gases. Repurposing natural gas pipeline systems to dedicated hydrogen networks can deliver substantial cost savings compared with building new hydrogen pipelines.[2] Regulators should consider cost-benefit analyses to assess whether or not to decommission an asset, including potential benefits if repurposed for use with low-carbon gases.

Collaboration among G20 countries can be beneficial to extend the usefulness of natural gas infrastructure through retrofits and repurposing. Such efforts can build on initiatives under way including: the industry-led Oil and Gas Climate Initiative; the International Methane Emissions Observatory created in 2021; and the IEA *Methane Tracker database* and analysis. A useful tool is *Driving Down Methane Leaks from the Oil and Gas Industry: A Regulatory Roadmap and Toolkit*. It offers a step-by-step guide for developing or updating regulations on methane. Its advice draws on analysis of how more than 50 countries, states or provinces – from the United States to Nigeria, from Iraq to China and Russia – have tackled methane emissions from a regulatory perspective.

Existing oil and gas infrastructure can be used for transport of carbon dioxide to oil and gas fields for permanent storage. Several companies are looking to ship CO_2 captured from their own operations by pipeline to other industrial and agricultural projects or for permanent offshore storage, such as at Snøhvit, a natural gas field in the Norwegian Sea with carbon capture and storage operations since 2007.

Overall, cost-effective use of existing oil/gas supply chains can boost the clean energy transition in hard-to-abate sectors and support the development and deployment of new technologies. The oil and gas industry works to minimise emissions from core operations, notably methane, and invests in technologies vital to energy transitions, such as CCUS in depleted oil and gas fields or for enhanced oil recovery, low-carbon hydrogen, biofuels, synthetic liquid fuels and offshore wind. Refineries can convert their facilities to biorefining and support the scale up of biofuels production by co-processing

[2] The 2020 European Hydrogen Backbone report estimates that the cost per kilometre of refurbished natural gas pipeline could be 67% lower compared to the cost of new hydrogen pipelines. The latest network development plan of Germany's TSO Association estimates that costs of new hydrogen pipelines would be almost nine-times higher compared to repurposed natural gas pipelines. See more information at: https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/.

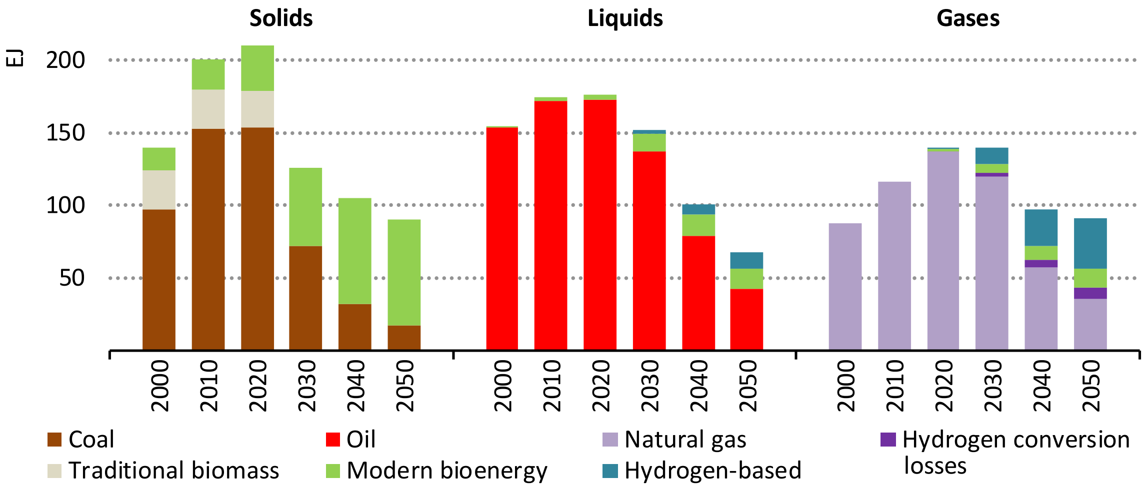
renewable feedstock together with petroleum as well as support midstream, marketing and blending activities, with the conversion or construction of required infrastructure.

Fossil fuels are currently used in co-generation and heating and cooling district systems in many countries. To date, policies have given limited attention to possible approaches to support of the use of renewables in these existing assets. At the end of 2019, only 49 countries – mostly within the European Union – had national targets for heating and cooling district systems using renewables, compared with 166 having goals for renewables-based power generation. A 2020 joint IRENA-IEA-REN21 study *Renewable Energy Policies in a Time of Transition: Heating and Cooling* describes five possible transformation pathways towards an acceleration of renewables-based heating and cooling district systems. They include renewables-based electrification, burning of renewable gases and sustainable biomass, as well as the direct use of solar thermal and geothermal heat, together with the enabling infrastructure.

5. Modernise oil security systems

Emissions from some sectors and sub-sectors are difficult to abate and will rely on fossil fuel use for some period. For example, while electric vehicles show promise in road transport, it is more challenging to reduce emissions from aviation and maritime shipping at the same speed. While the overall level of oil, gas and coal consumption will decline in clean energy transitions, this does not mean that fuel supply security concerns will dissipate. The figure below illustrates the fuel contribution to global supply in the 2000 to 2020 period and the outlook to 2050 in the net zero pathway.

Solid, liquid and gaseous fuels in 2000–2020 and in the Net-Zero Emissions by 2050 Scenario



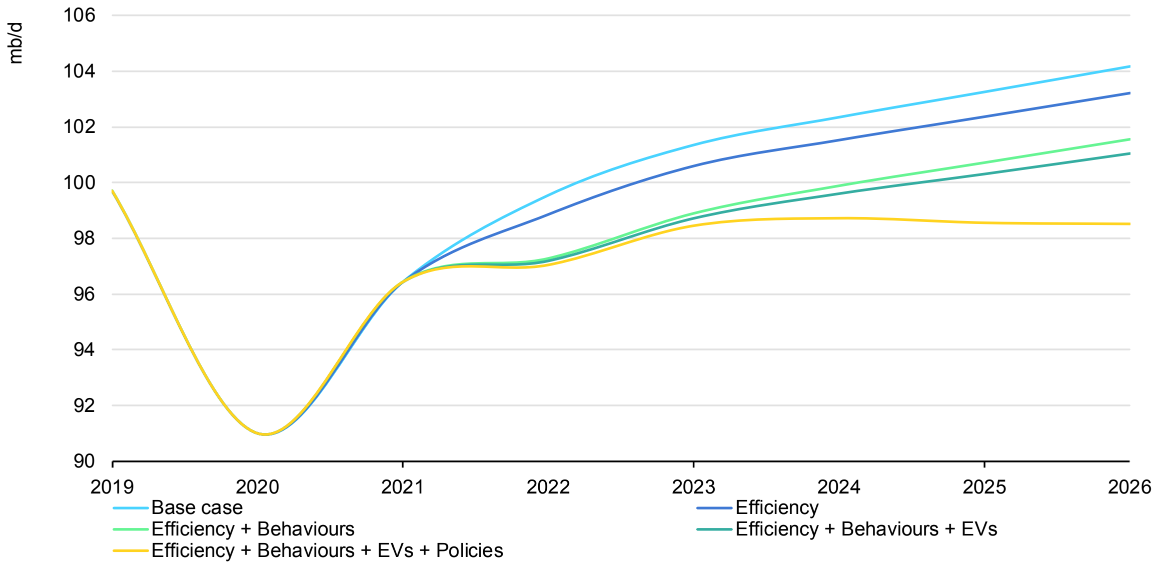
Notes: EJ= exajoule. Hydrogen conversion losses = consumption of natural gas when producing low-carbon merchant hydrogen using steam methane reforming. Hydrogen-based includes hydrogen, ammonia and synthetic fuels.
Source: IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

Changes along the clean energy pathway will have implications for producers and consumers alike. For example, if a decrease in oil supply due to under investment outpaces drops in demand, there is potential for market volatility. Traditional security concerns persist across a range of potential scenarios with variations in efficiency standards, behaviour, policy and electric vehicle assumptions, as illustrated in the figure below. Some producer economies may face a complex risk environment with oil and gas revenues in decline and strains on their economies, which may impact upstream spending and maintaining supplies.

Progress in clean energy transitions is already creating uncertainties for some actors in the energy sector. This is the case for conventional resource-holders as well as oil companies. While traditional supply activities decline, the expertise of the oil and natural gas industry fits well with technologies such as hydrogen, CCUS and offshore wind that are needed to tackle emissions in sectors where reductions are likely to be most challenging.

While the world will rely for some time on the adequacy of investment and supply in oil and gas, producer economies need to prepare for a time in which hydrocarbons may no longer be the main source of revenue. In the *Net Zero Roadmap*, no new oil and gas fields are needed and supplies become increasingly concentrated in a small number of low-cost producers. For oil, the Organization of the Petroleum Exporting Countries (OPEC) share in global oil supply is projected to increase from about one-third in recent years to slightly more than half by 2050. Yet annual per capita income from oil and natural gas in producer economies falls by about 75%, which could have knock-on societal effects. Structural reforms and new sources of revenue are needed.

Traditional security concerns persist across various scenarios of global oil demand



Notes: EVs = electric vehicles. Policies include: teleworking; higher level deployment of electric vehicles; fewer business trips by air; taxes on oil use; heating oil use is discouraged in residential and commercial applications; oil is phased out in the power sector; more recycling; and measures to curb the use of internal combustion engine cars in city centres.
Source: IEA (2021), *Oil 2021: Analysis and Forecast to 2026*.

Transitioning away from oil to cleaner energy sources will also accelerate changes in refining, with implications for security. There will be significant changes in the oil product mix. Transport fuel demand will fall while oil demand for petrochemical feedstock will decline at a much slower pace. The refinery sector and oil supply chain will need to adapt to dynamic changes in the product mix and continue to respond to the needs of the world's economies for oil products. If a regional refinery capacity shut-in occurs faster than a decline in regional demand for some refined oil products, it will be necessary to ensure adequate product storage capacity to cover a disruption in imports from increasingly more distant supply locations.

Biofuels are set to expand their role in clean energy transitions and need to be adequately taken into consideration in terms of security of supply. As biofuels gain a larger share in energy supply, new challenges emerge stemming from their production, blending, transportation and storage. Biofuels, like biodiesel, are less stable than oil and natural gas products and cannot be easily stored over long periods. The location of biofuel production and consumption can differ. Production may be affected by seasonal weather and climate impacts. Robust trade routes, supply chains and stockholdings are needed to guarantee biofuel supply security. Establishing transparent markets and sustainable supply chains will be important to ensure security of biofuel supply. As the world becomes more dependent on biofuels in hard to decarbonise sectors such as aviation and shipping, supply disruptions could potentially have the same devastating impacts on prices and economies as oil disruptions in the past. Well-designed sustainability criteria and governance can support the expansion of sustainable bioenergy use with a clear and long-term set of accountability rules for market players.

The oil emergency response systems of the IEA member countries will continue to be critical tools for ensuring oil supply security as the world progresses on clean energy pathways. This emergency response system should be evaluated in the context of the energy transitions to guarantee its viability in the evolving market. It should include an assessment of the appropriate level of emergency oil stocks and how the system can be broadened to include all major oil consumers, as the centre of gravity in oil consumption is shifting to emerging and developing countries.

6. Prepare for new and emerging risks to energy security

Governments need to ensure that emergency preparedness and response capabilities continue to be robust and responsive as energy systems become more digitalised, electrified and depend more on the availability of critical minerals.

Climate change resilience

Climate change resilience – defined as the ability to anticipate, absorb, accommodate and recover from adverse climate impacts – is an essential element of successful clean energy transitions. Changing climate patterns and extreme weather events pose an increasing threat to electricity security. Higher temperatures could decrease efficiency, change generation potential and affect demand for heating and cooling. Changes in precipitation patterns may alter generation output (peak and variability) while posing physical risks to transmission and distribution networks. Sea level rise can limit development of new assets and threaten existing electricity systems near coastlines.

In many countries the increasing frequency and/or intensity of natural disasters and extreme events such as heat and cold waves, wildfires, droughts, cyclones, hurricanes and floods, are a significant cause of large-scale power outages. For instance, in August 2020 exceptional electricity demand from air conditioners caused one of the largest revolving power cuts to consumers in nearly 20 years in California. Extreme cold weather can impact supply security, as was seen when exceptionally cold weather in February 2021 provoked massive electricity shortages in Texas. Such events demonstrate that existing infrastructure can be far from resilient, and also expose consumers to exorbitant energy price spikes.

The IEA outlined in its 2021 report *Electricity Security: Climate Resilience* the climate impacts on electricity systems and proposes a step-by-step application of measures for policy makers and key stakeholders to build the climate resilience of electricity systems. It underscores the benefits of climate resilience and the costs of climate impacts, which tend to be unevenly distributed across energy sectors and consumers. Governments should better monitor impacts, identify cost-effective resilience measures, including procurement provisions and RD&D support. For owners and operators of electricity systems such as utilities and grid companies to be able to direct investment in protecting their assets, regulations need to account for the preventative benefits of hardening energy infrastructure and related investments.

Digital resilience

Digitalisation is rapidly transforming energy systems. It can accelerate clean energy transitions by unlocking increased demand-response opportunities, integrating higher shares of variable renewables, and intelligent balancing of power supplies and demand such as via smart charging of electric vehicles. Fossil fuel supply chains have been highly automated with digital technologies. Investments in the expansion and digitalisation of smart grids need to increase in line with clean energy transition objectives.

In parallel, increased connectivity and automation raise security risks of cyberattacks. A malicious attack could trigger the loss of control over devices and processes in energy systems, in turn causing physical damage and widespread service disruptions. The ongoing expansion of connected devices and distributed energy resources compounds cybersecurity concerns.

While total prevention of cyberattacks is not attainable, energy systems can become more cyber resilient in order to withstand, adapt to and rapidly recover from incidents and attacks, while preserving the continuity of critical infrastructure operations. Governments are central to enhancing digital resilience. This includes raising awareness and working with stakeholders to continuously identify, manage and communicate emerging vulnerabilities and risks. National policies should facilitate partnerships and sector-wide collaboration, develop information exchange programmes and support research initiatives.

Governments can build and reinforce digital resilience through a range of policy and regulatory approaches, taking concrete steps to: institutionalise responsibilities and incentives; identify, manage and mitigate risks; monitor progress; and respond to and recover from disruptions, as elaborated in the recent IEA report *Electricity Security: Enhancing Cyber Resilience in Electricity Systems.*

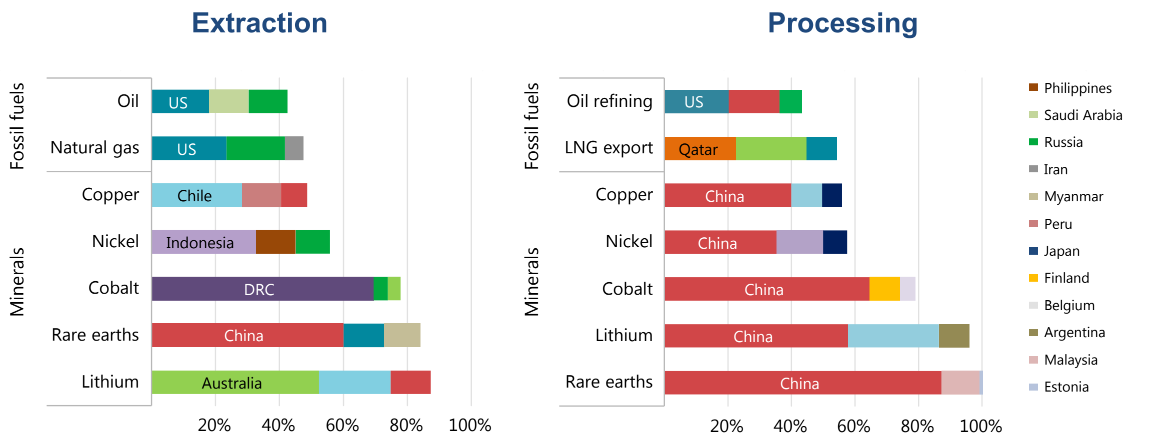
A wealth of existing risk management tools, security frameworks, technical measures and assessment approaches are available, which countries can take on board and tailor to particular circumstances. Collective security should be boosted by international co-operation, such as the G20 in sharing information on incident alerts and standards for best practices. This could include mechanisms for supply chain security of the critical hardware and software that support oil, gas and electricity system operations, such as certification based on international standards.

Critical minerals

The deployment of clean energy technologies relies on substantial quantities of critical minerals in adequate and timely supplies. The availability of critical minerals, such as lithium, cobalt, copper and nickel, is fundamental to manufacturing a variety of clean energy technologies. Such minerals also are widely used in many industrial and defence applications as well as in appliance manufacturing, which puts pressure and increased competition on the their limited production.

While the use of critical minerals in clean energy technologies varies by technology, the overall demand is substantial. For example, a typical electric car requires six-times the mineral inputs of a conventional car, and an onshore wind installation requires nine-times more minerals than a gas-fired plant of the same capacity. Lithium, cobalt and nickel are critical in battery manufacturing. Rare earth elements are vital for wind turbines and electric vehicles. Electricity networks consume huge amounts of copper and aluminium, while hydrogen electrolysers and fuel cells need nickel or platinum group metals. Copper is an essential element for almost all electricity-related technologies. Since 2010, the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as renewables take a higher share in total capacity additions. Meanwhile, the market is becoming more and more concentrated with supply shortages and price volatility.

Share of top three countries in production (extraction and processing) of selected minerals and fossil fuels, 2019



Note: US = United States; DRC = Democratic Republic of the Congo.
Source: IEA (2021), *The Role of Critical Minerals in Clean Energy Transition*.

Compared with fossil fuel supply, the supply chains for critical minerals are more complex and, in some cases, much less transparent. For lithium, cobalt and rare earth elements, the top-three producers control well over three-quarters of global output. In some cases, a single country is responsible for more than half of worldwide production, as shown in the figure. The Democratic Republic of the Congo accounts for about 70% of global production of cobalt. South Africa accounts for about 70% of platinum production (not shown in the figure). China accounted for 60% of global rare earth production in 2019 (albeit down from over 80% in the mid-2010s) and over 90% of its processing and refining capacity. The supply chains for copper and nickel are slightly more diverse, but still around half of global supply is concentrated in the top-three producing countries.

The transition to clean energy implies a shift from a fuel-intensive to a materials-intensive system. The transition brings new trade patterns, countries and geopolitical considerations into play, requiring policy actions to be reconsidered. The security of successful transitions will depend largely on the availability of critical minerals and the ability of manufacturers to supply adequate volumes of clean energy technologies, amid increased competition for access to these minerals. Disruptions in supply of critical minerals may delay or even halt the progress of clean energy transitions, leaving global energy systems fragmented and highly vulnerable. Significant risks may arise in several parts of the minerals supply chain, starting from increased mining needs and related environmental, social and governance concerns. Processing and refining of critical minerals can also be environmentally hazardous, and will require strict regulation and oversight for social acceptability, and to reduce uncertainties about supplies.

Governments have a variety of roles, domestic and international action, to strengthen supply security of critical minerals. First and foremost, governments should provide clear signals on targets for greenhouse gas emissions reductions and renewables supply, and start irreversible decarbonisation actions to create clarity on demand for critical minerals. Further, to support industry, governments may need to assess their procedures for mining critical minerals, conduct and share geological studies of prospective areas, and support RD&D of new technologies for critical mineral extraction, use, recycling and substitution. An adequate and well-trained workforce is needed for mining and refining. Other actions to achieve large-scale supply of critical minerals are providing public finance and guarantees, ensuring effective regulatory frameworks and gaining social acceptance. Standards for sustainability, achieved through international consensus, will also be necessary to avoid local environmental challenges, while recognising human labour rights and promoting local economic development.

7. Promote people-centred inclusive transitions

Inclusiveness for successful transitions

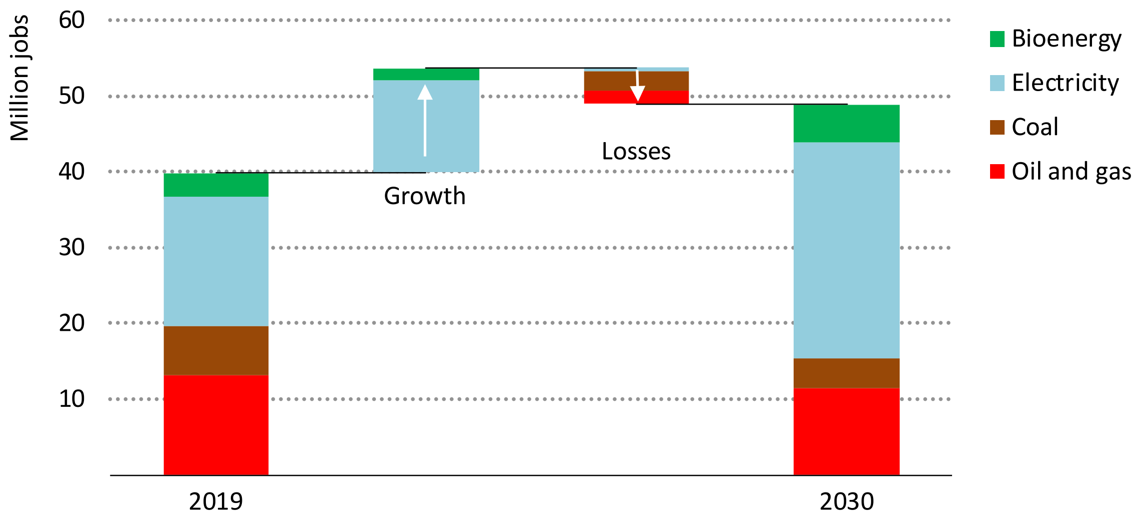
Global leaders acknowledge that energy transitions that focus on people and the benefits they will derive will be more inclusive, equitable and are more likely to succeed. As more countries embark on ambitious goals to accelerate the shift to clean energy, people will experience many changes in their daily lives. This includes a range of social and economic impacts on individuals, communities and businesses in terms of employment changes, affordability and fairness. At the same time, for clean energy transitions to maintain public support, they also need to enhance the security and reliability of supply and access to energy.

Good policies can enhance energy access and make it affordable particularly for the energy poor while improving living conditions with cleaner air and healthier homes. Policies can foster new avenues of employment and create sustainable jobs and careers, which can provide opportunities to those that are reliant on industries and fuels that are set to decline. Jobs need to be focused on supporting the reliability and resilience of energy systems.

Based on projections of the *Net Zero Roadmap*, jobs created would not necessarily be in the same area where jobs are lost, furthermore, the skill sets required for the clean energy jobs may not be directly transferable. Job losses would be most pronounced in communities that are heavily dependent on fossil fuel production and/or transformation activities. Transitions will inevitably affect certain sectors or communities disproportionately and will face risks from perceptions of inequity or exclusion. These will come together with many current contextual challenges, such as political polarisation, urban-rural divide, inequality and the Covid-19 crisis and resulting economic disruptions. Many countries, including both advanced and emerging economies that still heavily rely on fossil fuels, will face significant challenges in the transition.

Mobilising investment and finance will require wide and stable consensus to support national plans and infrastructure projects that foster structural shifts to more secure, resilient and cleaner energy systems. Preparing comprehensive and coherent policy frameworks that align energy, economic, labour, industrial, educational and social policies need to be an essential part of government efforts.

Global energy sector employment, Net-Zero Emissions by 2050 Scenario, 2019 and 2030



Source: IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

Governments around the world are already supporting communities and sectors with regard to mitigating the employment impacts of the transition and creating new job opportunities. Experience from coal mining transitions in several countries shows that clear planning, close co-ordination and engagement, and funding for support measures have been crucial to successfully facilitate disruptions and changes. Governments play a pivotal role to facilitate inclusive, social dialogues among public and private stakeholders, which aim to establish consensus on transition strategies and action plans.

Established in January 2021, the *Global Commission on People-Centred Clean Energy Transitions*[3] is examining best practice policies to ensure energy transitions are people-centred, equitable and inclusive, with a focus on concrete experiences. The Commission is developing a set of actionable recommendations that will enhance global approaches to people-centred clean energy transitions.

[3] In January 2021, the Global Commission was convened by the executive director of the IEA with the prime minister of Denmark as its honorary patron. The commission's aim is to put people at the heart of clean energy transitions. Its primary focus is on how best to empower citizens and ensure they benefit from the opportunities and navigate disruptions that arise. The commission is chaired by the Danish Minister of Climate, Energy and Utilities and co-chaired by the Minister for Petroleum and Energy of Senegal. Its high-level panel comprises energy and climate ministers and leading figures from international organisations and key sectors of society.

Energy access and energy poverty reduction

Affordability in the clean energy transition is critical to improve energy access and because social support is needed to achieve larger scale deployment of clean energy infrastructure.

The G20 has emphasised the need to provide universal energy access and reduce energy poverty, as a core pillar of energy security. Today 790 million people lack access to electricity and 2.6 billion people lack access to clean cooking. This leads to millions of premature deaths every year, impedes economic development and is a big barrier to progress on gender equality and education.

The *Net Zero Roadmap* shows that a global approach in the energy sector can achieve universal energy access by 2030, at a cost equivalent to less than 1% of energy investments to 2030 while contributing less than 0.2% to CO_2 emissions. There is no trade-off between reducing emissions and achieving universal energy access. A range of options are considered for reaching universal access to electricity; about 45% of the affected people gain access via a new connection to main grids, 30% from mini-grids and 25% from stand-alone solutions. Off-grid or mini-grid solutions are almost all renewables based.

For clean cooking, in the *Net Zero Roadmap*, 55% of those gaining access by 2030 do so through improved biomass cook stoves, biogas or ethanol, 25% through liquefied petroleum gas and 20% via electric cooking solutions. G20 governments and donors need to put expanding access at the heart of recovery plans and programmes.

Producer economies

Oil and natural gas revenues in producer economies are expected to decline as clean energy transitions advance. Structural reforms and new sources of revenue are needed. For producer economies that rely on oil and gas revenue to finance broad economic activities, an immediate focus on economic diversification is imperative. The Covid-19 pandemic induced a downturn in oil demand in 2020, which could hold important lessons for producer economies. The commensurate decline in revenues meant that producer economies were hit harder than most others. In the Middle East and North Africa, for instance, the GDP of net oil and gas exporters are expected to have shrunk by 6.6% in 2020, compared to 1% for the net importers. In the most severely affected countries, poverty rates are estimated to have doubled in just one year.

Building more resilient economies to help mitigate the potential decline in fossil fuel revenue would help producer countries respond to the challenges associated with clean energy transitions. Energy could play a large role in their efforts to diversify, particularly in those looking to leverage existing advantages across their energy value chains towards cleaner energy forms. The ability of producer economies to reform and diversify is crucial if they are not to be left behind. The alternative is the prospect for a disjointed transition in which socio-economic and political pressures could build to the point of becoming a significant threat. While traditional supply activities decline, the expertise of the oil and natural gas industry fits well with technologies such as hydrogen, CCUS and offshore wind that are needed to tackle emissions in sectors where reductions are likely to be most challenging.

Investment in energy efficiency and renewables could have significant positive impacts on jobs and employment in producer economies. However, it is equally important to note that the loss of jobs in hydrocarbons due to the structural decrease in demand implied by the transitions is only one consideration. Compensating for the loss of revenues to the state (oil and gas revenue can account for up to 98% of fiscal revenues in some producer economies) is a challenging endeavour. The revenues from oil and gas enable large public sector employment, and social and health programmes. As revenues and the jobs that they underpin decline, widespread unemployment could stymy economic diversification[4].

[4] The revenue implications of the clean energy transitions are not limited to the producer economies. Taxes can exceed 60% of the fuel price in some countries, and declining demand would impede this significant revenue stream.

Conclusions: Seven principles for security of clean energy transitions

Energy efficiency is the "first fuel". It is a fundamental building block of cost-efficient clean energy transitions to make energy systems more resilient and affordable, and to lower emissions. Many energy efficiency measures for industry, buildings, appliances and transport are well known, cost-effective and ready to be put into service now. They should be a priority in order to realise short-term emissions targets by 2030. G20 countries should take immediate action to drive a major near-term push to reap the unexploited efficiency potential across all available technologies. They should scale up cross-government efforts to mobilise finance, strengthen efficiency standards, broaden digitalisation and other measures to achieve energy intensity improvements of 4% per year in the period to 2030 – about three-times the average pace of improvement over the last two decades. After 2030, a continued focus on energy efficiency needs to remain as a cost-effective and fundamental approach to reduce energy consumption in all end-use sectors as well as a hedge against technology and policy uncertainties on the pathway to a low-carbon energy future. **The G20 should constructively engage in dialogue and co-operation to effectively implement energy efficiency policies and measures,** including through the *Energy Efficiency Hub*.

Progress on the clean energy pathway is being led by the **electricity sector**, which has multiple examples of what interconnected policy action and technology deployment can achieve. Renewables are central to electrification and clean energy transitions. With sharp cost reductions over the last decade, solar PV is consistently cheaper than new coal- or gas-fired power plants in most countries. Hydropower remains the largest renewable source of electricity, but solar PV is the main driver of growth, followed by onshore and offshore wind. **Deployment of solar PV and wind must be accelerated** to reach targets set for 2030 and beyond. Government actions to hasten renewables deployment include setting effective policy and regulatory frameworks, favourable fiscal incentives where needed and market development tools such as auction and procurement schemes.

Boosting the uptake of renewables-based generation requires their secure integration into electricity systems, as well as social acceptance. The pace of change puts a premium on robust grids, dispatchable power plants, storage technologies and demand-response measures to provide flexibility and resilience in power systems. Existing low-carbon dispatchable generation sources are important contributors to power system operations on the clean energy pathway. In some cases, lifetime extensions of these plants may be cost-effective options. In other cases, some plants may be retrofitted or repurposed to contribute to the clean energy transition, for example, co-firing with biomass or possibly ammonia in coal plants. Regional electricity market integration and interconnections can expand opportunities to ensure power system flexible and resilience.

G20 countries need to promote increased investment in clean electricity generation, network infrastructure and end-use sectors. Enabling infrastructure and technologies are vital to transform the energy system. Governments have a decisive role by providing strategic vision, policy signals and public finance that spur action by private actors, and catalysing innovation. Policies need to be designed to send market signals that stimulate new business models and private spending, Mobilising the capital for large-scale infrastructure calls for closer co-operation between developers, investors, public financial institutions and governments. Private initiative and capital is vital to clean energy transitions, nonetheless, the majority of energy investment around the world is still made in response to conditions set by governments.

Diversity in the power generation mix is fundamental for security of supply. The transition calls for major increases in all sources of flexibility: batteries, demand response and low-carbon flexible power plants, supported by smarter and more digital electricity networks. The resilience of electricity systems to cyberattacks and other emerging threats needs to be enhanced. Investment in the diversification of energy delivery routes, types, and sources will help create redundancy of infrastructure and therefore resilience against new security risks.

G20 countries need to maintain vigilance on security of fossil fuel supply during clean energy transitions. Reductions in fossil fuel demand may be outpaced by decreases in supply due to under investment. Fossil fuel supply may become concentrated in a limited number of low-cost producer countries. The oil security system of the IEA member countries will continue to be critical as it needs to respond to market evolution. The G20 should promote the modernisation of oil security systems and continue to boost transparency and open and competitive energy markets to address energy security concerns during the transitions.

To **ensure the cost-effective use of existing fossil fuel assets and infrastructure** for secure and affordable energy transitions, **their emissions must be mitigated**. G20 countries need to share experience and policy best practices for retrofitting and/or repurposing of oil, gas and coal assets, including methane emissions reductions and technology investment to accommodate low-carbon fuels, notably hydrogen, ammonia and biofuels, to support flexibility of energy systems and foster environmentally sound and equitable transitions.

Adverse impacts on energy systems from climate change could spark unplanned outages, which can thwart clean energy transitions by undermining public confidence in the availability of stable and affordable energy supply. **G20 countries should create conducive policy and regulatory frameworks that encourage owners of energy infrastructure to take appropriate weather-proofing measures relative to climate and extreme weather variabilities**.

With increased electrification and rising shares of variable renewables, digitalisation and smart grids become key to support the transformation of power systems, making digital resilience ever more paramount. **G20 countries should foster collaboration on digital security** by sharing information on incident alerts and standards for best practices. This should include endorsing steps to improve supply chain security of critical hardware and software that support oil, gas and electricity system operations, such as certification based upon existing international standards.

As dependence on renewables and other clean energy technologies, such as batteries and electric vehicles increases, **energy security broadens from fuel to material-related concerns**. Ensuring resilient global supply chains should be at the forefront of the economic and trade collaboration of the G20. **Critical minerals** are needed for almost all clean energy technologies. G20 countries need to review and improve policies related to critical mineral mining, social acceptance and investment. Public finance and guarantees, regulatory frameworks and transparency are fundamental. G20 countries need to boost R&D efforts to reuse, recycle and develop substitutes for some clean energy technologies and their materials. Developing an international framework in this area will help all G20 countries to ensure supply of critical minerals. The G20 should consider now how to best encourage the creation and promotion of resilient, responsible, and integrated supply chains to avoid supply disruptions of key energy resource minerals. The G20 representing the leading economies should be at the forefront of this issue, promoting transparency in supply chains as well as free, open, and fair markets for the critical minerals and metals necessary to the achieve the step increase needed in capacity to realize our clean energy goals.

Clean energy transitions that are **people-centred and inclusive** will ensure that all persons benefit. A focus on people can ensure that transitions are seen as fair and inclusive, can create new jobs, enhance energy access and energy security to the benefit of all. G20 countries can benefit from exchanging best practices in order to design and implement better policies.

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